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## Summary talk: How serious are the problems faced by CDM: cusps, thin disks, and halo substructure

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**Abstract.** This is a summary of the discussion in Panel I of IAU Symposium 220 on Dark Matter in Galaxies. The panel topics and panellists were as follows – Cusps Theory: Julio Navarro; Cusps Observations: Erwin de Blok, Rob Swaters; Substructure Observations: Mario Mateo; Substructure Theory: James Taylor, Shude Mao. In addition to the talks by the panellists and the discussion among them, there was a good deal of discussion with the audience. Despite the differences of opinion expressed I think a consensus emerged, and I try to summarize it here.

### 1. Introduction

When the first high-resolution simulations of cold dark matter halos became available (e.g. Dubinski & Carlberg 1991), they had a central density profile approximately  $\rho(r) \propto r^{-1}$ , which has come to be known as the central “cusp.” It was soon pointed out by Flores & Primack (1994) and by Moore (1994) that this central behavior was inconsistent with the HI observations of dwarf galaxies that were then becoming available, which suggested that the central density is roughly constant. Flores & Primack (1994) pointed out that the first cluster lensing observations (Tyson et al. 1990) also appeared to be inconsistent with a  $r^{-1}$  central cusp. Many additional rotation curves of low surface brightness (LSB) galaxies were measured, and they also were claimed to imply that the central density of these galaxies is rather flat. It was subsequently pointed out that the HI observations of galaxies were affected by finite resolution (“beam smearing”), and that when this was taken into account the disagreement with simulations is alleviated (see e.g. van den Bosch et al. 2000, van den Bosch & Swaters 2001). More recently, high resolution H $\alpha$  and CO rotation curves have been obtained for a number of dwarf and LSB galaxies (e.g. de Blok et al. 2001, McGaugh et al. 2001, Swaters et al. 2003, Bolatto et al. 2002, and the papers presented at this Symposium), and there is hope that this will clarify the situation.

Meanwhile, theorists have done simulations with increasing resolution. On the basis of simulations with tens of thousands of particles per dark matter halo, Navarro, Frenk, & White (1996, 1997, NFW) showed that halos from galaxy to cluster scales have density profiles that are described fairly well by the fitting function

$$\rho_{NFW}(r) \equiv \rho_s(r/r_s)^{-1}(1+r/r_s)^{-2}$$

and that the halo concentration

$$c \equiv R_{200}/r_s$$

(where  $R_{200}$  is the radius within which the average halo density is 200 times the critical density) is a declining function of the mass of the halo. Subsequently, James Bullock and Risa Wechsler improved our understanding of halo evolution in their dissertation research with me, which included analyzing thousands of dark matter halos in a high-resolution dissipationless cosmological simulation by Anatoly Klypin and Andrey Kravtsov. Bullock et al. (2001), defining the (virial) concentration

$$c_{vir} \equiv R_{vir}/r_s$$

(where  $R_{vir}$  is the virial radius, see Bullock et al. 2001 and Bryan & Norman 1998), found that at fixed halo mass  $c_{vir}$  varies with redshift  $z$  as  $(1+z)^{-1}$ , and developed an approximate mathematical model that explained the dependence on mass and redshift. (An alternative model was proposed in Eke et al. 2001, but it appears to be inconsistent with a recent simulation of small-mass halos by Colin et al. 2003.) Wechsler et al. (2002) determined many halo structural merger trees, and showed that the central scale radius  $r_s$  is typically set during the early phase of a halo's evolution when its mass is growing rapidly, while  $c_{vir}$  subsequently grows with  $R_{vir}$  during the later slow mass accretion phase (see also Zhao et al. 2003). Higher resolution simulations with roughly a million particles per halo gave central density profiles  $\rho(r) \propto r^\alpha$  with  $\alpha$  as steep as -1.5 (Moore et al. 1999a, Ghigna et al. 2000, Klypin et al. 2001) although more recent very high resolution simulations are finding less steep central profiles with  $\alpha \approx -1$  or shallower (Power et al. 2002, Stoehr et al. 2003, Navarro these proceedings).

## 2. Cusps: Observations

The following remarks attempt to summarize the panel discussion.

- With the increasing availability of high resolution H $\alpha$  and CO observations, beam smearing is no longer a serious problem.
- Observational resolution of nearby dwarfs and LSBs has exceeded the theoretical resolution of simulations.
- Different observers often agree on  $V(r)$  and on the index  $\alpha$  of the same galaxy (where  $\rho(r) \propto r^\alpha$ ).
- Disagreement remains (Swaters et al. 2003, de Blok et al. 2003, and these proceedings) on the importance of systematic effects such as slit width, position, and alignment (all of which bias the slope of the inner rotation curve to appear shallower than it really is).
- Two-dimensional data is becoming available at galaxy centers, including data with exquisite resolution (e.g. Bolatto, these proceedings).
- Measured inner slopes  $\alpha$  mostly lie in the range 0 to -1.

- A slope  $\alpha = -1.5$  is clearly inconsistent with the observations.
- The NFW value  $\alpha = -1$  is consistent with some galaxies, possibly consistent with others, and inconsistent with a significant number.

### 3. Cusps: Theory

- Recent high resolution simulations (see especially Navarro, these proceedings) have inner slopes inconsistent with  $\alpha = -1.5$  (as found by Moore et al. 1999a, Ghigna et al. 2000) and possibly even with the NFW value  $\alpha = -1$ .
- The inner slopes are not converging to any  $\alpha$ , but appear to grow shallower at smaller radii (Navarro, these proceedings; Navarro et al. 2003). However, the simulations still do not have sufficient resolution to see whether  $\alpha$  actually becomes shallower than -1 at small radii.
- Observing test particle motion in a triaxial halo from  $\Lambda$ CDM simulations results in a range of 2D velocity profiles similar to observed ones (Navarro, these proceedings).
- The mean density  $\Delta_{V/2}$  inside the radius  $r_{V/2}$  (where the rotation velocity reaches half the maximum observed value) appears to be somewhat smaller than the  $\Lambda$ CDM prediction with  $\sigma_8 = 0.9$ , but more consistent with  $\Lambda$ CDM with  $\sigma_8 = 0.7$  (Alam, Bullock, Weinberg 2002, Zentner & Bullock 2002) using the Bullock et al. (2001) model.<sup>1</sup>
- The scatter in the concentrations or  $\Delta_{V/2}$  values indicated by the observations of LSB and dwarf galaxies appears to be greater than that of the simulations. (See e.g. Fig. 11 of Hayashi et. al. 2003.)

Although it was not discussed during this panel, I want to mention some new work on the central cusp problem for clusters. Sand, Treu, & Ellis (2002) measured the density profile in the center of cluster MS2137-23 with gravitational lensing and velocity dispersion, removed the stellar contribution with a reasonable M/L, and found  $\rho_{DM}(r) \propto r^\alpha$  with  $\alpha \approx -0.35$ , in apparent contradiction to the expected NFW  $\alpha = -1$  for CDM. (See also Treu, these proceedings, and Sand et al. 2003.) Similar results were found for Abell 2199 by Kelson et al. (2002). The apparent disagreement with CDM worsens if adiabatic compression of the dark matter by the infalling baryons is considered (Blumenthal et al. 1986). However, dynamical friction of the dense galaxies moving in the smooth background of the cluster dark matter counteracts the effect of adiabatic compression, and leads to energy transfer from the galaxies to the dark matter which heats up the central cuspy dark matter and softens the cusp. N-body

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<sup>1</sup>Note however that  $\Lambda$ CDM with  $\sigma_8 = 0.9$  is consistent with the early ionization indicated by WMAP polarization (e.g. Ciardi, Ferrara, & White 2003), but a tilted model with  $\sigma_8 = 0.7$  has too little early star formation to produce the observed optical depth unless there is some sort of exotic ionization (Somerville, Bullock, & Livio 2003).

simulations (El-Zant et al. 2003) show that the dark matter distribution can become very shallow with  $\alpha \approx -0.3$  for a cluster like MS2137, in agreement with observations.

#### **4. Halo Substructure**

- Many fewer satellite galaxies are seen around the Milky Way and M31 than the number of halos predicted (Kauffmann, White, & Guiderdoni 1993; Klypin et al. 1999  $\Lambda$ CDM; Moore et al. 1999b SCDM).
- But for  $\Lambda$ CDM the discrepancy arises only for satellites smaller than LMC and SMC, and small satellites are expected to form stars very inefficiently (Bullock, Kravtsov, & Weinberg 2000, Somerville 2002, Benson et al. 2003a).
- Larger ratios of dwarfs/giants are predicted and observed in cluster cores, where a higher fraction of dwarf halos should have collapsed before the redshift of reionization, than in lower density regions like the local group (Tully et al. 2002, Benson et al. 2003a).
- It is important to check that such dwarf galaxies have expected properties. For example, at least some of their stars should be old.
- Concern: do the predicted radial distributions of halo substructures agree with observations? Observed satellites may be located at smaller radii than the subhalos found in simulations, but the observational and simulation data sets are still small.
- “Milli-lensing” by DM halo substructure appears to be required to account for anomalous flux ratios in radio lensing (see e.g. contributions by Mao, Schechter, and Schneider in these proceedings).<sup>2</sup>
- Concern: is there enough halo substructure in the inner  $\sim 10$  kpc, where it appears to be needed to account for such lensing?

#### **5. Disk Thickening**

Another concern is whether halo substructure will thicken disks more than observed? Although this was not discussed in the panel, a recent paper by Benson et al. (2003b) calibrates an analytic model against N-body simulations to calculate the heating of galactic disks by infalling satellites. It concludes that this is a small effect, with most of the disk thickening due to the gravitational scattering

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<sup>2</sup>Mao & Schneider 1988 suggested that something was wrong with the magnification ratios of Q1422. Metcalf & Madau 2001 and Chiba 2002 pointed out that dark matter substructure should be detectable through magnification ratios of strong lenses, Metcalf & Zhao 2002 showed that the measured ratios do not agree with simple models, and Dalal & Kochanek 2002 attempted to use this to measure the density of substructure. Recent relevant papers include Schechter & Wambsganss 2002, Kochanek & Dalal 2003, Keeton et al. 2003, and Metcalf et al. 2003.

of stars by molecular clouds. The observed thicknesses of the disks of spiral galaxies would then be consistent with the substructure in dark matter halos predicted by the standard  $\Lambda$ CDM model. It would be desirable to check these results with higher-resolution simulations.

## 6. Conclusions

- **Cusps:** There has been tremendous progress on observed velocity fields, and also real progress in improving simulations. *Observed* simulations may agree with observed velocities in galaxy centers better than seemed likely a few years ago. But it is something of a scandal that there is still so little theoretical understanding of dark matter halo central behavior, although people are making progress on this problem (e.g. Dekel et al. 2003ab). It is likely that poorly understood astrophysics will turn out to be relevant (e.g. Combes, these proceedings; Binney, these proceedings).
- **Substructure:** A challenge appears to be turning into a triumph for CDM, since it appears that roughly the amount of substructure predicted by  $\Lambda$ CDM is required to account for the number of satellites seen and for the flux anomalies observed in radio lensing. The main remaining concern is whether the predicted radial distribution of substructure agrees with lensing and observed satellites. Much work remains to be done to test the theory quantitatively.
- **Disk thickening:** Not obviously a problem.

There are no better alternatives to  $\Lambda$ CDM that have yet been invented. Those that have been investigated in detail, such as warm dark matter (WDM) and self-interacting dark matter (SIDM), fare much worse despite having additional parameters (see e.g. Primack 2003). Invent new ones, if you can!

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